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Diagnosis of Radial Deformation and Axial Displacement Faults in Power Transformer Windings using X-ray and Compton Backscatter Imaging

Abstract: - Continuous and uninterrupted transmission and distribution of electrical energy is highly dependent on the flawless operation of power transformers. Failure of these critical components can lead to network power interruptions and consequently have severe detrimental consequences. Therefore, timely detection and diagnosis of power transformer faults is crucial not only to prevent the escalation of faults but also to minimize repair and maintenance costs.

Conventional methods for inspecting windings faults have limitations such as the need to take the transformer out of service, unreliable results, and the addition of auxiliary devices inside the transformer, such as dielectric windows. In contrast, the proposed method in this paper utilizes a Compton Backscatter Imaging (CBI) or X-Ray Transmission (XRT) device located outside the transformer, eliminating the need for any additional equipment. This enables online scanning of any number of transformers to assess their health status and identify the type, extent, and progression of potential internal faults. Experimental results demonstrate the feasibility of the proposed method for detecting radial deformation and axial displacement and disk space variations faults of varying magnitudes and locations in both high-voltage and low-voltage windings of power transformers.

Keywords: Power transformers, Winding faults, Radial deformation, Axial displacement, Disk space variation, Compton backscatter imaging, X-ray transmission, Online inspection.

I. INTRODUCTION

Power transformers are vital components of the electrical grid, and their reliable operation is paramount for uninterrupted power supply. However, they are susceptible to various defects, categorized as electrical and mechanical. This paper focuses on mechanical defects within the transformer windings, specifically radial deformation, axial displacement, and disk space variation [1, 2]. These mechanical anomalies often trigger a cascade effect, leading to electrical problems. The compromised insulation due to mechanical stress weakens the windings, introducing electrical faults [3]. If left undetected and unaddressed, these faults can progressively worsen, ultimately forcing the transformer offline and disrupting the power grid.

Therefore, the timely and accurate diagnosis of mechanical defects in power transformer windings is crucial. Effective monitoring systems play a key role in this process, aiming to first identify the presence of a fault and then pinpoint its type, location, and severity. Several methods have been explored for detecting the aforementioned mechanical winding defects. Frequency response analysis (FRA) is one such technique that has received significant attention [4-6]. However, implementing FRA online within the power network presents technical and operational challenges. Additionally, offline testing with FRA requires taking the transformer out of service, and the interpretation of the resulting frequency response data remains a subject of debate among researchers [7-9].

In 2007, the idea of using electromagnetic waves for online fault detection in power transformer was first proposed [10]. In this method, the electromagnetic waves are radiated by an antenna to the transformer winding. After hitting the transformer winding, these waves are returned and the returned waves are received and stored by the antenna [11].

By using different characteristics of reflected waves such as scattering parameter in the frequency domain, different indices are defined and by using classification methods, the transformer fault is detected [12, 13].

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Since this method is based on comparing the signal of the healthy state of the transformer with the faulty state, it requires a database of the return signal in different fault states. In other words, it is necessary to first implement various defects on the real transformer or in the simulation environment, and after implementing the method, the stored signals for similar transformers should be used [13]. The high sensitivity of the method, the significant error in the simulation and the impracticality of implementing various defects on a real transformer were among the problems of this method.

In 2012, the radar imaging method using electromagnetic waves was introduced [14]. In this method, it is no longer necessary to form a database, and as a result, one of the problems of the previous methods was improved. For radar imaging, the process of sending and receiving the same signal was done as before, but by moving the set of transmitter and receiver antennas along the height of the transformer and repeating the process of sending and receiving, a two-dimensional image of the transformer was formed using the Kirchhoff method [15]. By processing this image, it was possible to detect defects along the height or the circumference of the high voltage winding [16].

Due to the movement of the antenna, there was a need to install a dielectric window, which was simulated and implemented in [17]. Since the movement of the antenna in the inner environment of the transformer was problem, the hyperbolic method was introduced, based on the difference of the signal reached to the two stationary antennas at the top and bottom of the winding, the location of the defect was obtained [18]. In all the introduced methods based on electromagnetic waves, there were three serious problems:

- The need to change the structure of the transformer in order to install a dielectric window on the transformer tank, because it is not possible for waves to pass through the transformer tank.
- The insertion of a device such as antenna to the inner environment of the transformer, which changes the field order inside the tank environment and makes it necessary to review the design of the transformer.
- The impossibility of detecting and locating faults in the inner winding of the transformer.

In order to solve the problems of the previous methods, a new method has been introduced in this paper so that not only there is no need to change the structure or introduce a foreign body into the internal environment of the transformer, but also it is possible to detect the defects of the low voltage winding. In this method, by using Compton's backscattering property, a proper image of the transformer is obtained by sending and receiving X-rays with implementing the source and detector outside the transformer as this waves can pass through the tank.

Today, the use of Compton imaging is widely used in industry and medicine. In [19], the authors examined the backscattered X-ray image of a car with threatening materials embedded in the trunk and inside the doors and fenders. In [20], Compton X-ray imaging was used to evaluate the condition of different parts of passenger planes. In clinical radiography with X-ray backscatter, three-dimensional images are provided, and can provide very useful information to the phisicians in diagnosis [21]. This radiation has been used in early cancer diagnosis and better diagnosis with monochromatic imaging, phototherapy and radiation therapy targeting cancer cells on a nano scale [22]. In this research, this radiation will be used to diagnose power transformer defects.

X-ray radiographic imaging has already been studied and used to check power grid equipment. The use of X-ray imaging for continuous monitoring of possible defects in substation equipment and protective devices, especially partial discharge equipment, is suggested [23]. Also, X-ray digital radiography has been simulated and revealed in the defects of the insulating environment and GIS [24]. In [25], technical requirements are presented for X-ray digital scan radiography in the inspection of high voltage equipment in operation.

In this paper, investigation of localizing the radial deformation and axial displacement and disk space variation defects of the transformer winding is carried out through Compton backscattered imaging simulation, experimental tests using 130 kV digital x-ray source and experimental tests using 250 kV analog x-ray source. The rest of the article is as follows: First, imaging by Compton backscattered beam is briefly explained. Then, in the simulation environment, using the Open-MC Monte Carlo code, a transformer with two high-voltage and low-voltage windings considering a transformer core is simply modelled, and the defect on the high-voltage winding is detected. The results show that not only the dimensions of the defect can be detected, but also its location will be determined. Using this method, it is possible to perform the image formation process by using a source and detector outside the transformer tank, and by determining the dose of the source according to the thickness of different parts of the transformer and the tank, a clear image can be obtained.

In the experimental results section, to detect the deformation of the windings in power transformers, small-scale model windings are made, and a radiographic test is performed on them with an X-ray camera with transmitted rays. In these experiments, the X-ray camera is placed on one side of the transformer and the radiology film on the other side and outside the tank, that the rays travel across the width of the transformer. These experiments are performed with 130 kV digital and 250 kV analog cameras to observe the effect of X-ray source energy on the images. Finally, from the simulation of compton backscatter imaging and X-ray imaging, it is observed that these images confirm each other and can also provide a suitable image of the location and amount of defects inside the transformer.

II. Spectrum of electromagnetic radiation

According to Planck's equation, that is calculated and summarized in table 1, the wavelength, frequency and energy of the radiation spectrum of electromagnetic waves of electric and electromagnetic fields in the transformer and even microwave radio waves in the environment and background compared to the spectrum of hard X-ray waves (6 mega electron volts in this research) and high-energy gamma rays (Cobalt 60 with an energy of 1.22 MeV in this paper) are observed. It can be seen that electric and electromagnetic fields and microwave radio waves have no effect on imaging with X-rays and gamma rays. As a result, whether the winding under study is energized or not, there is no effect on the results of using proposed methods, so the procedure of proposed method can be implemented for the online power transformer in future.

Table 1- wavelength, frequency and energy of electromagnetic radiation spectrum

Electromagnetic Radiation	Frequency (Hz)	Energy (keV)	Electromagnetic Radiation Wavelength (m)
X-Ray	1.45×10^{18}	6000	2×10^{-10}
Gamma-Ray	0.3×10^{18}	1220	1×10^{-9}
Radio waves	1×10^{11}	4.14×10^{-7}	30
Electric field and electromagnetic waves in transformer	50	1.45×10^{-16}	6×10^{6}

III. Compton backscatter imaging for internal inspection of transformers

Compton backscatter imaging (CBI) offers a promising non-destructive inspection (NDI) technique for visualizing the internal structures of objects. This method leverages the Compton scattering phenomenon, where high-energy photons (X-rays or gamma-rays) interact with charged particles (primarily electrons) within a material. As illustrated in Figure 1 [26], a photon with wavelength λ collides with a stationary electron and converts into a scattered photon with lower energy and a different direction, while the electron is recoiled and becomes a recoil electron. Detection of these scattered photons forms the basis of image formation in CBI.

A significant advantage of CBI lies in its ability to image objects accessible from only one side. Additionally, CBI proves valuable for inspecting large objects impractical for conventional transmission X-ray techniques. This capability holds particular relevance for transformers, where crucial components reside within a sealed steel and oil tank, hindering direct internal observation. By employing the principle of Compton backscattered radiation, CBI offers the potential to glean valuable information about the transformer's internal state.

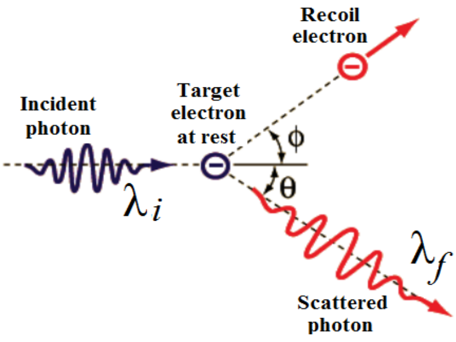


Figure 1 - Compton scattering geometry [26]

Figure 1 shows the Compton scattering. Scattered photon energy (E_2) is calculated from momentum conservation (P) and energy conservation. The energy of the scattered photon (E_2), which is a function of the energy of the incident photon (E_1) and the angle of the incident photon with the scattered photon (θ), is obtained from Equation 1 [26].

$$E_2 = \frac{E_1}{1+\frac{E_1}{E_0}\left(1-\cos\theta\right)} \tag{1}$$

where E_0 is the rest state energy of the electron and is equal to 511 KeV.

The differential photon scattering cross section for a non-polarized photon beam by an electron under angle (θ) is expressed by the Klein-Neshina relation in the following equation [26]:

$$\frac{d_e\sigma_c}{d\Omega} = r_o^2\left[\frac{1}{1+\alpha\left(1-\cos\theta\right)}\right]^3\left(\frac{1+\cos\theta}{2}\right)\times\left[1+\frac{\alpha^2(1-\cos\theta)^2}{\left(1+\cos^2\theta\right)\left[1+\alpha\left(1-\cos\theta\right)\right]}\right] \tag{2}$$

where r_0 is the classical radius of the electron and α is the photon energy for the rest energy of the electron and their values are:

$$r_o = 2.81794\ (fm) = 2.81794\times10^{-15}\ (m) \tag{3}$$

$$\alpha = \frac{\mathrm{E_i}}{\mathrm{E_0}} \tag{4}$$

Also:

$$d\Omega = 2\pi\sin\theta d\theta \tag{5}$$

If Equation 1 is integrated in all angles (θ), equation 6 is obtained:

$${}_e\sigma_c = \frac{\pi r_o^2}{\alpha}\left\{\left[1-\frac{2\left(\alpha+1\right)}{\alpha^2}\right]Ln\left(2\alpha+1\right)+\frac{1}{2}+\frac{4}{\alpha}-\frac{1}{2(2\alpha+1)^2}\right\} \tag{6}$$

In Equation 6, the microscopic cross-section of Compton photon scattering per electron (${}_{e}\sigma_{c}$) has been obtained. The intensity of Compton scattering (D_e) depends on the electron density of the environment, and this itself depends on the product of the density of atoms N by the number of electrons of each atom Z in other words:

$$D_e = NZ \tag{7}$$

Since the electron density of the medium varies for different materials, this method can be used to identify the deformation of objects with good sensitivity. In other words, after passing through the transformer tank and oil, the radiation hits the electrons of the copper windings, then according to the Compton phenomenon, it causes the return radiation to deviate or reflect the radiation. This reflected ray leaves the transformer oil and tank and reaches the detector. The reflected ray carries the information of the winding.This information can be indicative of axial displacement and radial deformation defects in the transformer winding.

IV. Introducing the OpenMC code simulation environment

In this paper, Open-MC Monte Carlo code is used for simulation. The Monte Carlo method is one of the calculation algorithms that rely on repeated random sampling to calculate their results. This multipurpose time-independent code tracks neutron, photon, electron transport in any 3D geometry and presents the particle transport results as a function of energy.

The working method of the OPEN-MC code is as follows; A particle while passing through a material may undergo different scattering interactions before absorbing or escaping from that environment. This code uses zero and one random numbers to determine the type of interaction between the particle and matter, the amount of energy lost in each reaction, and the scattering of the particle. The reactions that may occur after the primary photon collides with matter in the OPEN-MC code are: Scattering, photon production-entanglement and end of history-photon release-photon absorption-Compton scattering.

In order to use the OPEN-MC code, the necessary and accurate information must be given to the program through an input file, which makes it possible to obtain accurate and reliable answers in the output file. Obviously, in order to achieve the desired result, this information, including the geometry of the system, the materials used and their distribution, the source and its characteristics, etc., should match the test system as much as possible.

The desired information in the input file is selected from the OPEN-MC code input cards and included in the input file. A card means an OPEN-MC input line that contains the necessary instructions on how to simulate the geometry of the problem, various demands, etc. Among the quantities that can be calculated in OPEN-MC, we can refer to the number of photons absorbed or released from the environment, or in other words, the output. This output is calculated based on statistics, so the answers are normalized to 1 [27].

V. Transformer model

The base of the proposed method is comparing the image of transformer winding when it is sound and has not been started to work, with the image when any fault is occurred. In other words, when a transformer is installed and before starting operating of it, an image is created using proposed method. Then, continuous or in determined maintenance periods, the proposed method is aaplyed and a second image is created. If there is any difference between second image and the first one, fault can be detected. In this paper, in order to model the transformer, the following assumptions are considered:

A- In the windings deformation, the tank, core and oil have been seen in Open-MC simulation program.

B - By changing the angle of the source of the rays and the detector, as well as changing the power of the source of the rays, we adjust the depth of penetration and the desired section to check the transformer.

C - The location of imaging devices can be changed, for example in four different directions of the power transformer. With these changes, images are taken from desired places of the transformer and possible defects are observed.

D - In imaging with Compton backscattered rays of the gamma source, by changing the location of the source and the detector to the front, back, left and right, more appropriate images can be obtained, where the location and extent of the defect can be seen.

Figure 2 shows a simple schematic of a single-phase transformer model in the Open-MC program. To be close to reality, a steel tank with a thickness of 0.8 cm containing oil is also included. The core of the bobbin is in the central cylinder with a diameter of 20 cm made of steel and on it 5 layers of copper with a thickness of 0.5 cm as a low voltage winding with a total thickness of 2.5 cm and then 5 layers of copper with a thickness of 0.5 cm as a high voltage winding with a total thickness of 2.5 cm is considered so that the total diameter of the winding with the core is 30 cm.

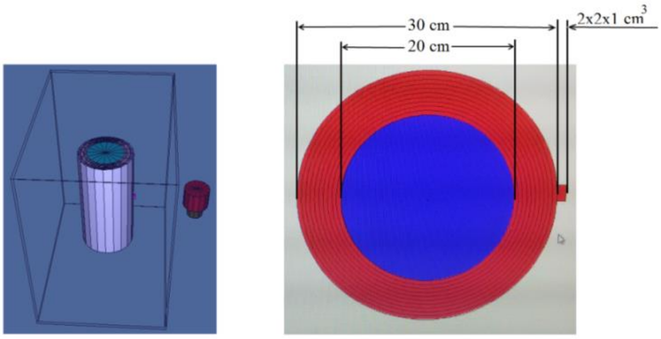


Figure 2 - Schematic of transformer next to HPGe detector with Open-MC code

As mentioned before,in this article, the criteria for error detection is to compare the healthy state with the defective state. By observing the change of the image compared to the healthy state, it is possible to understand the existence of an error. The windings in the healthy state of the transformer are in the form of concentric circles, but in the event of a radial deformation defect in each winding, these circles change to one to four elliptical states in that winding [12]. The resulted image can be analyzed with different image processing methods [17].

In order to consider the radial defect, it is assumed that due to the problems on the transformer, a cube-shaped defect with dimensions of 2x2 square centimeters and a thickness of 1 cm was created at the middle of the copper winding on the cylinder of the copper winding, which is shown in Figure 2. High-purity germanium (HPGe) detector and source are at an optimal 90° angle for optimal signal collection outside the hypothetical transformer.

VI. Simulation with X-ray compton backscattered

As shown in Figure 3, with the number of 90,000 X-rays and the duration of imaging (about 17.27 seconds) and the beam energy of 6 mega electron volts, the image of the outward buckling located on the high voltage winding is determined. By increasing the duration of imaging, the image is obtained with greater clarity.

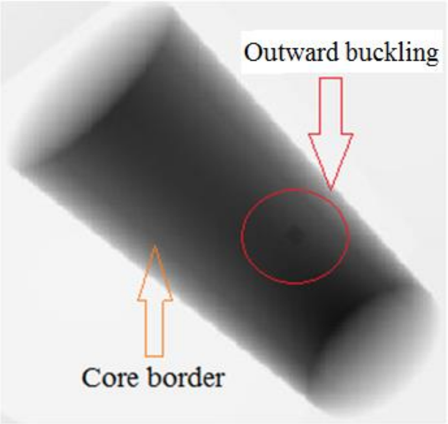


Figure 3 - The image of the outward buckling on the simulation winding with X-ray backscatter

VII. Simulation with gamma-ray compton backscattered

In the simulation of gamma rays, Cobalt 60 has been used as a gamma source for Compton backscatter imaging. The simulation specifications are according to Table 2. Considering that in the Monte Carlo code, OPEN-MC continues only the defined number of rays until the calculation error reaches less than 0.1%, so with 10 million defined rays, up to about 1 million has followed the particle. In Figure 4, the image with excellent resolution, and the outward buckling with the size of 3.33% of the diameter of the winding can be seen.

Table 2 - Radiographic specifications

Description	Specification
Source type	Co 60
Source Energy	1.332 MeV
The number of defined source particles	10 million
The number of particles of the investigated source	998,499
Detector type	HPGe
The angle of the source and the detector	90 deg.
The duration of the radiation effect on the object	275.85 sec

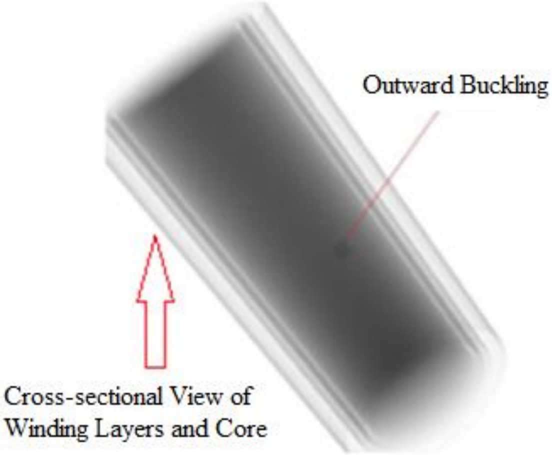


Figure 4 - Simulation of the assumed winding with Gamma-ray compton backscattered

VIII. Experimental results

Considering the effective components of the transformer in imaging, including; transformer tank, copper windings and iron core with their high thickness, for X-rays to pass through different layers of the transformer, a hard X-ray source with high electromagnetic energy is needed. Due to the high human dose of the hard X-ray source during imaging, it is necessary to pay attention to the risks of exposure to radiation and use appropriate protection. Although one of the advantages of X-ray camera over gamma is that the source is active only during operation.

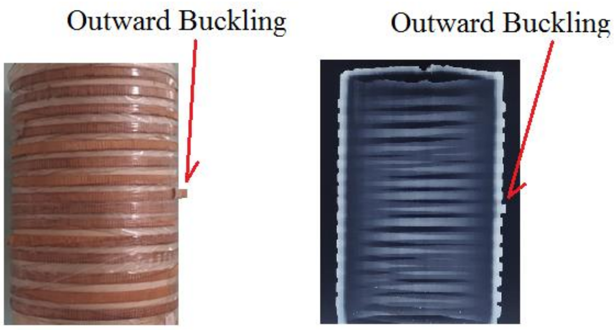
In order to perform imaging to detect the radial deformation of windings in a phontom of power transformers and on a small scale model, windings were made and a radiographic test was performed on them with an X-ray camera.

A. Imaging of high voltage winding model with 130 kV X-ray source

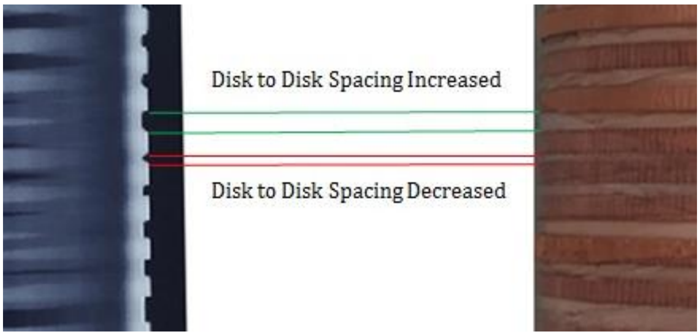
According to Figure 5-A, the model used for HV winding consist of an iron pipe with an inner diameter of 130 mm and a thickness of 4 mm, which is surrounded by a winding of copper belt with a thickness of 1.2 mm and a cross section of 8×1.2 mm^2. To detect the radial deformation of the high voltage winding, a deformation model is placed on the eighth ring of the winding. Voltage, current and irradiation time of X-ray can be adjusted according to Table 3. In the radiograph image of Figure 5-b, the outward buckling of radial deformation on the eighth ring, and Figure 5-c, the axial disk displacement can be clearly seen on the winding.

Tabe 3- The setting values of the imaging device

Quantity	Value
Voltage	130 kV
Current	200 mA
Irradiation duration	0.63 sec



a) Modeled winding **b) Radiograph image of the winding**



c) Disk space variation

Figure 5: Modeled winding and its radiograph image

Since this imaging device has limited voltage, current and radiation duration, it is only suitable for imaging high voltage winding (outer layer winding) which is good for the radial problem and axial disk displacement on the winding and especially in the edge of the winding. So, if necessary, by changing the locations of the X-ray source and the X-ray detector, a more appropriate image can be obtained. The radiograph image in Figure 5-b shows that the voltage and power of the radiographic device is important and effective on power transformers imaging. In comparison, for large power transformers that have a very thick and complex structure, it is better to use Compton backscatter imaging.

B. Imaging of a model containing core, LV and HV windings with 250 kV X-ray source

To model the low voltage winding, as shown in Figure 6-a, an iron pipe with an inner diameter of 130 mm and a thickness of 4 mm, on which a winding of copper belt with a cross section of 8×1.2 mm square is wrapped.

To model the high voltage winding, as shown in Figure 6-b, a polyethylene pipe with an inner diameter of 160 mm and a thickness of 3 mm, on which a winding of copper wire with a thickness of 1.7 mm is wrapped.

a- Low voltage **b- High voltage**

Figure 6: Modeled windings

To show the radial defects of the windings, a piece of copper is cosidered on the low voltage wire and several pieces of wire aer cosidered horizantally and vertically on the high voltage winding, which is shown in Figure 6.

The iron pipe as the core, and the low voltage winding on it, is placed inside the high voltage winding coaxially. Then, the X-ray radiography test is performed by observing the standard vertical distance between the beryllium valve of the X-ray machine and the raw radiography film. Considering that in the X-ray device controller, the thickness of iron is the basis, by converting the thickness of the copper wire and busbars to the equivalent thickness of iron, the thickness of 26.2 mm is entered in the controller of the X-ray device, and the parameters of current, voltage and radiography time corresponding to this part are calculated and applied by the controller device according to Table 4.

Tabe 4 - The setting values of the imaging device

Quantity	Value
Voltage	210 kV
Current	1.5 mA
Irradiation duration	168 sec

In Figure 7, the radiograph image of low voltage and high voltage windings can be seen, according to the thickness of the wires. Also, four light lines along the length (middle) and four light lines along the radius (left side) with a thickness of 1.7 mm can be seen as a bright area as a defect in the radial deformation of the high voltage winding. At the bottom of the radiograph image, a bright area with dimensions of 85×1.2 square mm, in the longitudinal direction of the low voltage winding, can also be seen as a defect of the radial deformation of the low voltage winding.

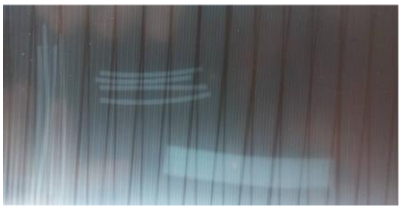


Figure 7. Radiograph of the low voltage winding inside the high voltage winding with images of defects on both of them.

IX. CONCLUSIONS

This paper investigates the potential of X-ray and gamma-ray Compton backscatter imaging for the detection of internal defects in power transformer windings during operation. The proposed method leverages the high-energy nature of Compton backscattered radiation to penetrate the transformer enclosure and image the internal structure of the windings.

The study explores three aspects:

Simulation: The feasibility of the technique was evaluated through simulations using the Open-MC Monte Carlo code. Simulations modeled the interaction of X-ray or gamma-ray sources with a winding cylinder, employing an HPGe detector at an optimized angle of 90 degrees for optimal signal collection. The simulations employed a rotational approach around all three axes (X, Y, and Z) to comprehensively scan the winding volume and identify potential defect signatures.

Experimental Validation: To validate the idea of using X-ray imaging for detection of winding deformation and displacement, experimental tests were conducted using a physical model of transformer windings. Two X-ray sources were investigated: a 130 kV digital source and a 250 kV analog source. Radiographic imaging was performed using a traditional X-ray camera with transmitted radiation. In these tests, the X-ray source was positioned on one side of the transformer model, while the X-ray film was placed on the opposite exterior side.

Sensitivity Analysis: The experiments revealed limitations associated with the source energy. A lower-energy digital X-ray source successfully imaged defects in the outer layers of the high voltage (HV) windings. However, due to insufficient penetration depth, the image quality for inner layers, particularly the low voltage (LV) windings, was significantly compromised.

The study highlights the importance of optimizing X-ray source parameters like voltage, current, and exposure duration to achieve optimal image clarity and defect visibility. By employing a higher-power X-ray source, the experiment successfully visualized radial defects in both the HV and LV windings within the sample model. Also, due to the bulky structure of the transformer, the Compton backscattering method is better than the transmission X-ray method.

Furthermore, the study emphasizes the potential for defect detection in transformers with any number of winding layers. By establishing a baseline image of the transformer in a healthy state and comparing it with subsequent images obtained during operation, deviations caused by radial deformation, axial displacement, disk space variations, or other winding abnormalities can be identified. This approach offers a promising non-intrusive diagnostic technique for ensuring the health and reliability of power transformers.

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